Renewable and Sustainable Energy Reviews 20 (2013) 611–618

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Comparative assessment of road transport technologies

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ARTICLE INFO

Article history:
Received 5 August 2012
Received in revised form
20 December 2012
Accepted 21 December 2012
Available online 24 January 2013

Keywords:
Road transport
Fuel
Energy
Atmospheric emissions
GHG
MCDM
Uncertainty

ABSTRACT

The aim of the paper is to assess energy technologies in road transport sector in terms of atmospheric emissions and costs and to indicate the most competitive and environmentally friendly transport technologies. The main tasks of the paper are: to develop the multi-criteria framework for comparative assessment of energy technologies in road transport and to apply MCDM methods for the transport technologies assessment. One of the MCDM methods, viz. the interval TOPSIS method, is employed in order to tackle the uncertain criteria. The assessment framework allows comparing road transport technologies in terms of their environmental and economic impacts and facilitates decision making process in transport sector. The main indicators selected for technologies assessment are: private costs and life cycle emissions of the main pollutants (GHG; particulates, NO*x*, CO, HCs). The ranking of road transport technologies based on private costs and atmospheric emissions allowed prioritizing these technologies in terms of environmental friendliness the lowest costs. However the extent, capacity, and quality of road infrastructure affects the overall level of transportation activity, which in turn affects how much energy is consumed by vehicles and the amount of greenhouse gases (GHG) emitted. The paper presents the impact of transportation infrastructure on GHG emissions from road vehicles and policy implications of performed assessment.

Contents

1. Introduction

Combating climate change is a top priority for the European Union. Transport is responsible for around a quarter of EU greenhouse gas emissions making it the second biggest greenhouse gas emitting sector after energy generation sector. While emissions from other sectors are generally falling, those from transport have increased 36% since 1990. Therefore GHG emission reduction from motor vehicles is a major challenge for EU climate change mitigation policy. Modest increases in vehicle efficiency have been offset by increased number of vehicle fleet and total travel [1,2,3,4,5].

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.12.021

There are few main approaches for reducing GHG emissions from road transport:

- Improving fuel economy by using hybrid electric vehicle (HEV).
- Implementing low carbon fuel such as bioethanol or biodiesel.
- Substitution of the portion of petroleum by electricity used to power vehicle by using plug-in hybrid vehicle (PHEV).
- Improvement of road infrastructure, better traffic management, smart transportation behavior or eco driving practices etc.

The future development and deployment of new road transport technologies in EU highly depends on carbon constraints set by international climate change mitigation regimes [2]. As climate change mitigation is the central environmental policy in EU the long-term assessment of new road transport technologies is useful for policy makers taking into account the main criteria, namely private (fuel and motor vehicle) costs and life cycle atmospheric emissions the most important of which are GHG emissions [2]. Such assessment would help policy makers to identify the most promising motor vehicles in terms of costs and atmospheric emissions and to develop policy tools to promote them. The aim of the paper is to find the cheapest and environmentally friendly motor vehicles in terms of private (fuel and vehicle) costs. The impact of road infrastructure on GHG emissions from motor vehicles is also addressed in the paper and policy recommendations are provided.

The branch of operation research, namely multi-criteria decision making (MCDM) offers a variety of computational techniques for integrated prioritization of decision alternatives. According to [6] the MCDM can also be successfully employed in sustainable energy policy-making. Moreover, MCDM methods relying on interval-data aggregation [7,8] are suitable for evaluation of uncertain phenomena. One of MCDM, the TOPSIS (Technique for order preference by similarity to an ideal solution) method extended with interval number [9] is applied in this study. Initially, the crisp TOPSIS method was presented in [10]. More specifically, TOPSIS relies on measurements of distances from hypothetic ideal alternatives for each alternative considered.

The paper is organized as follows: Section 2 describes the focal issues of the transport policy. Section 3 focuses on the interval TOPSIS method which was employed for the analysis. The following Section 4 presents the results of multi-criteria assessment of the road transport technologies. Section 5 discusses the impact of road infrastructure on GHG emissions. Finally, Section 6 proposes some policy implications for sustainable road transport development.

2. Transport policy

Transport is responsible for 23% of global energy-related greenhouse gas emissions, and its contribution is increasing rapidly. Climate mitigation has thus moved to the heart of transport policy and indeed to the heart of EU policy. The process of establishing a new Common Transport Policy for the EU is essentially about creating this vision and then filling it out with policies that can deliver its goals. This will be the real challenge in creating a pathway towards a de-carbonised transport sector. Some issues have already been addressed. New passenger cars have been put on a trajectory towards emissions of 95 g CO_2/km by 2020—almost a 50% cut compared to 1990. Unfortunately traffic levels are growing at around the same rate as average emissions are projected to fall, meaning that the net effect may still be far from what we need.

Sustainably produced biofuels can also contribute to diversification of energy sources and supplies. Biofuels currently account for about 2% of global fuel consumption for transport. A growing number of countries support domestic production of biodiesel and ethanol through subsidies, reduced taxes and regulations requiring mandatory blending of biofuels with petrol or diesel fuel. However, only a limited number of countries have favorable climatic conditions and the land and water resources necessary for large-scale biofuel production [10,11].

In recent years, a growing number of motor vehicle manufacturers have announced plans or started production and sales of hybrid and plug-in electric vehicles, primarily for use in urban areas. In China, and in a growing number of other countries, electric bicycles have become popular. Electric vehicles are quiet, produce no emissions at the point of use and are, therefore, popular for use indoors (e.g. in hospitals, airports, exhibition halls and similar facilities) and in environmentally protected areas. Several motor vehicle manufacturers have also successfully tested and demonstrated hydrogen-based emission-free fuel-cell technologies [12–14].

When assessing greenhouse gas mitigation options, it is important to consider life cycle impacts. Electricity and hydrogen can offer important opportunities to decarbonize the transport energy system, but the realization of full-cycle carbon reduction depends on the way in which the electricity and hydrogen are produced. Greater use of electricity or hydrogen for private motor vehicles would be sustainable only if future systems are increasingly based on renewable sources of energy. A gradual transition towards greater use of electric vehicles will also only advance sustainable development if the batteries necessary for on-board energy storage are affordable and if the growing quantities of lithium needed in these batteries are produced in a sustainable way.

The decoupling of transport services and energy use is important for mitigating climate change and improving efficiency. In light of the recent volatility in international energy prices, the development of alternative fuels, produced in a sustainable way, including compressed natural gas, ethanol and biodiesel, can offer diversification of transport fuels as part of an array of options for sustainable transport. There is also need to deploy cleaner fossil fuels. Enhancing the modernization of transport technology and redefining the understanding of mobility, including thinking in terms of providing mobility services and promoting climate-friendly mobility management, can curb the projected growth in greenhouse gas emissions and support sustainable development.

The European Commission has a comprehensive strategy to reduce CO_2 emissions from new cars and vans sold in the European Union, to ensure that the EU meets its greenhouse gas emission targets under the Kyoto Protocol and beyond. This strategy, which was adopted in 2007, aims to tackle CO_2 emissions from both the production and consumer sides and is designed to help the EU reach its long-established objective of limiting average CO_2 emissions from new cars to 120 g per km by 2012—a reduction of around 25% from 2006 levels. The goal of reducing new car emissions to 120 gCO_2/km by 2012, as defined in the strategy, is however not likely to be achieved because some measures have been implemented late. Despite a low probability of achieving the 2012 target, the strategy, and the measures it includes, has played an important role in reducing CO_2 emissions from light-duty vehicles.

EU policies in place aiming to lower emissions from the road sector:

- a strategy is in place to reduce emissions from cars and vans, including emissions targets for new vehicles;
- a target is in place to reduce the greenhouse gas intensity of fuels;
- rolling resistance limits and tire labelling requirements have been introduced and tire pressure monitors made mandatory on new vehicles; and

- public authorities are required to take account of life time energy use and CO_2 emissions when procuring vehicles.

In addition to these measures influencing vehicle emissions, it is also necessary to ensure that account is taken of the impact of transport policy actions and measures on atmospheric emissions reduction. This helps to ensure consistent signals to transport users and vehicle manufacturers and to achieve atmospheric emissions reductions at lowest cost.

As there is a wide range of road transport technologies between biofuels and hybrid cars each of them specific with different fuels, selection of the most promising technology becomes very important issue in development of the transport policy. Indeed, it is the selection of the best transport technologies that should be promoted by policy tools in terms of atmospheric emissions and cost reduction. As atmospheric emissions from road transport are usually provided as the range of values comparative assessment of road transport technologies needs some sophisticated MCDA tools. The TOPSIS method for interval data is described in the following chapter.

3. TOPSIS method for interval data

The following description of TOPSIS for interval data is presented according to [9]. Let us assume, there are $i=1,2,...,m$ alternatives evaluated according to $j=1,2,...,n$ criteria. Each criterion can be assigned with a respective weight w_j such that $\sum_j w_j = 1$. The uncertain response of the i-th alternative on the j-th criterion is expressed in interval number $\tilde{x}_{ij} = [x_{ij}^l, x_{ij}^u]$, where x_{ij}^l and x_{ij}^u are the lower and the upper bounds respectively of an uncertain response. In this case a value x_{ij} is considered to be uniformly distributed within the interval, bounded by the lower limit, x_{ij}^l, and the upper limit, x_{ij}^u. Furthermore, let B and C are the two subsets of benefit and coast criteria, respectively. Specifically, the benefit (cost) criteria are assumed to approach higher (lower) values as the phenomenon under analysis approaches its optimal state.

The multiple criteria involved in the MCDM are usually expressed in different dimensions, e.g. monetary units, indices, factors etc. One therefore needs to establish a single common dimension for all the indicators (criteria) so that they could be aggregated in a reasonable way. The interval TOPSIS method relies on the modified vector normalization, which takes into account not only the minima or maxima observed for the criteria set, but also the distribution of the decision variables with their ranges. The initial decision matrix $\tilde{X} = \tilde{x}_{ij}$ is turned into the normalized decision matrix $\tilde{N} = \tilde{n}_{ij}$ in the following way:

$$n_{ij}^l = w_j x_{ij}^l \Big/ \sqrt{\sum_{i=1}^{m} \left[\left(x_{ij}^l\right)^2 + \left(x_{ij}^u\right)^2 \right]}, \ \forall i,\ j;$$

$$n_{ij}^u = w_j x_{ij}^u \Big/ \sqrt{\sum_{i=1}^{m} \left[\left(x_{ij}^l\right)^2 + \left(x_{ij}^u\right)^2 \right]}, \ \forall i,\ j. \tag{1}$$

From now on, the ranges of normalized interval numbers belong to an intervals [0, 1]. Furthermore, at this stage they can be multiplied by the respective weights, w_j.

The TOPSIS method belongs to the class of the MCDM methods which rely on the reference point approach. As for interval TOPSIS, the two hypothetic ideal solutions are found in order to perform a multi-criteria comparison. Consequently, the positive ideal solution, A^+, as well as the negative ideal solution, A^-, are obtained as:

$$A^+ = \{v_1^+, v_2^+, \cdots, v_n^+\} = \left\{ \left(\max_i n_{ij}^u | j \in B \right), \left(\min_i n_{ij}^l | j \in C \right) \right\},$$

$$A^- = \{v_1^-, v_2^-, \cdots, v_n^-\} = \left\{ \left(\min_i n_{ij}^l | j \in B \right), \left(\max_i n_{ij}^u | j \in C \right) \right\}, \tag{2}$$

where B and C stand for sets of benefit and cost criteria, respectively.

The performance of each alternative under consideration is assessed in terms of both the positive and negative ideal solutions. As it was mentioned before, the two ideal solutions define the two hypothetical ideal alternatives. Thereafter, the Euclidean distances from the latter two ideal alternatives are calculated for each i-th alternative

$$S_i^+ = \sqrt{\sum_{j \in B} \left(n_{ij}^l - v_j^+\right)^2 + \sum_{j \in C} \left(n_{ij}^u - v_j^+\right)^2},$$

$$S_i^- = \sqrt{\sum_{j \in B} \left(n_{ij}^u - v_j^-\right)^2 + \sum_{j \in C} \left(n_{ij}^l - v_j^-\right)^2}. \tag{3}$$

Finally, each alternative is given a closeness coefficient, which is measured as a relative proximity to the negative ideal solution

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}, \ \forall i. \tag{4}$$

The closeness coefficient approaches its lower bound, i.e. zero, if a certain alternative gets more similar to the negative ideal solution (alternative), and increases if the former alternative becomes remoter to the negative ideal solutions. Thus, the alternatives peculiar with higher values of the closeness coefficient (CC_i) are attributed with higher ranks.

4. Assessment of transport technologies

The main indicators or criteria for energy technologies assessment will be private costs of and life cycle emissions of the main pollutants (GHG; particulates, NOx, CO, HCs). The background for the selection of these criteria is EU transport policy described in Section 2. The motor vehicles have different private costs and environmental characteristics having impact on sustainability of these transport technologies. Therefore the main transport technologies will be compared according these indicators and ranked seeking to define the cheapest and environmentally most friendless motor vehicles. The development of alternative options in motor vehicles encompasses two approaches. The first involves the development of cleaner fuels that can be used with conventional engines. The second approach has been to develop partial or complete alternatives to the internal combustion engine. Therefore, we can classify cleaner vehicles in one of two ways: according to the fuel and according to the technology. The main options are therefore as follows:

4.1. *Cleaner vehicle fuels:*

- Biofuels—fuels produced from plant or animal oils including biodiesel and bioethanol.
- Gaseous fuels—fuels usually produced from fossil-fuel sources including compressed natural gas (CNG) and liquefied petroleum gas (LPG).
- Electricity—electricity can be generated using fossil or nuclear fuels, or from renewable sources.
- Hydrogen—like electricity, hydrogen is a secondary form of energy, which can be derived from renewable and non-renewable sources.

4.2. *Cleaner vehicle technologies*

- Battery-electric or BEV—electricity can be used to charge an on-board battery. When required, electrical energy is drawn

from the cells and converted to motive power by the use of an electric motor. These can be few types (Av-BEV based on average electricity mix: coal, gas, nuclear and renewable pathways and based on renewables Re-BEV).

- Hybrid-electric or HEV—a conventional engine is used to generate electricity on-board the vehicle. Motive power is provided via a mechanical drive-train and/or using electric motors via an electric drive.
- Fuel cell-electric—if hydrogen and oxygen (from the air) are fed into a fuel cell, a voltage difference is produced which can be used to drive an electric current, which in turn can operate an electric motor. This can be used to power a fuel cell vehicle.

In order to reduce vehicle emissions (from vehicle operation), regulations have been introduced that set mandatory limits for what are known as the regulated pollutants. These include carbon monoxide (CO), nitrogen oxides (NO*x*), hydrocarbons (HC) and particulate matter less than 10 μm in size (PM_{10}). The estimates of life cycle GHG, particulate (PM10), NO*x*, CO and hydrocarbons (HC) for the different mode of cars are given in Table 1 [15]. The life cycle air emissions from transport sector depend strongly upon details of supply chain, production techniques, forestry and agriculture practices, transport distance etc. The wide range of emissions per km is related with the type of car, i.e. size. Usually five types of passengers car classes are being considered: city car, super mini, small family car, large family car and the biggest cars SUV 4×4. For petrol vehicles, these are: city car (<900 kg), supermini (900–1200 kg), small family/MPV (1100–1350 kg), large family/MPV(1300–1700 kg) and SUV 4×4(>1600 kg).

The range of current private costs of road transport technologies were evaluated in EURcnt/vehicle km based on information about litres/vehicle provided by various data sources [16–19]. The price of gasoline and diesel is based on the average motor fuel cost in Lithuania in 2012. The costs of electricity for hybrid cars were assed based on average electricity price in Lithuanian in 2012. The average vehicle costs were assessed based on the average price of various motor vehicles in Lithuania assuming the average car ride of the car (50000 km/year) and the average life-time of the car -10 years. These costs for biofuels vary widely depending on the size of the passengers car types as in the case of air emissions. The data on private costs for motor vehicles is presented in Table 2.

The multi-criteria assessment of energy technologies for road transport technologies was based on data from Tables 1 and 2. As one can note, data in table are rather uncertain. Hence, we employed the interval TOPSIS method described in Section 3 for the analysis. Accordingly, the decision matrix (Table 3) was defined. As one can note, it contains five emission criteria and one cost criterion, six criteria in total. All of the criteria are to be minimized.

In order to deal with uncertainties and to check the sensitivity of the results, the three weight sets were defined: (1) the group of emission criteria and cost criterion were attributed with the equal weights viz. 0.5 and that value was further distributed across the five emission indicators; (2) for environmental approach the most of significance, namely 80%, was given to emission criteria and (3) for consumer-oriented approach the greatest significance of 80% was attributed to the private cost criterion. The weight vectors are presented in Table 4.

The initial data matrix was normalized and weighted. Firstly, Eq. (1) was employed to normalize the data. Thereafter the ideal solutions were found by identifying the minimal lower bound and the maximal upper bound for each of the cost criteria (cf. Eq. (2)). Note that the ideal solutions are crisp values rather than interval ones. These data for assessment under equal weight approach are given in Table 5.

The distances of each alternative were found with respect to Eq. (3), whereas closeness coefficients were obtained by employing Eq. (4). Thus, the considered road transport technologies were prioritized with respect to decreasing value of the closeness coefficient.

As it was already said the road transport technologies were assessed in terms of the three weight sets, with first treating both criteria equally, second putting the most of significance on GHG mitigation, and third—on the private costs. Accordingly, the ranking was reiterated three times with different weights. Table 6 presents the final results.

As one can note, the best option according to holistic (equal weight) and environmental approach is renewable-based battery-electric vehicles (Re-BEV), whereas customers would prefer biodiesel from rapeseed. Indeed, the first two approaches suggest biodiesel as the third-best option. Diesel, biodiesel, compressed natural gas (CNG), and liquefied petroleum gas (LPG)were those road transport technologies preferred by customers due to lower

Table 1
Emissions of road transport technologies, in g/vehicle km.

Life cycle emissions	GHG	PM10	NO_x	CO	HCs
HEV	100–400	0.001–0.035	0.1–0.3	0.1–0.5	0.3–1.1
Av BEV	125–300	0.035–0.135	0.18–0.7	0.1–0.4	0.18–0.6
Re BEV	25–80	0.005–0.018	0.05–0.15	0.05–0.1	0.05–0.15
LPG	125–450	0.007–0.035	0.17–0.37	0.5–1.2	0.18–0.65
CNG	120–420	0.01–0.025	0.05–0.2	0.49–1.0	0.5–1.5
Petrol	125–500	0.010–0.035	0.1–0.4	0.49–1.0	0.4–1.42
Diesel	115–430	0.01–0.06	0.25–0.62	0.20–0.5	0.15–0.62
Bioethanol	80–350	0.023–0.120	0.38–1.2	1–3.5	0.19–0.48
Biodiesel	70–300	0.005–0.07	0.44–1.1	0.20–0.75	0.38–1.2

Table 2
Private costs of motor vehicle in 2020, EURcnt/kWh.

	The range of fuel costs			Average electricity cost			Average vehicle costs, EURcnt/km	The range of total private costs, EURcnt/vehicle km
	EUR/l	Litres/vehicle km	EURcnt/vehicle km	EURcnt/kWh	kWh/vehicle km	EURcnt/vehicle km		
HEV	1.5	0.057–0.067	8.55–9.75	–	–	–	9	17.55–18.75
Av-BEV	1.5	0.042–0.049	6,3–7.35	13	0.2	2.6	9.1	18–19.05
Re-BEV	1.5	0.02–0.022	3–3.3	13	0.3	3.9	12.2	18.8–19.4
Petrol	1.5	0.08–0.1	12–15	–	–	–	7.2	19.2–22.2
Diesel	1.3	0.06–0.075	7.8–9.6	–	–	–	7.0	14.8–16.6
Bioethanol	1.2	0.08–0.1	9.6–12	–	–	–	7.2	16.8–19.2
Biodiesel	0.92	0.06–0.075	5.52–6.9	–	–	–	7.0	12.5–13.9
LPG	0.7	0.09–0.128	6.3–8.96	–	–	–	8.0	14.3–17.0
CNG	0.53	0.09–0.11	4.8–5.83	–	–	–	8.0	12.5–13.8

Table 3
Interval decision matrix for integrated assessment of road transport technologies.

	GHG MIN	PM10 MIN	NO_x MIN	CO MIN	HCs MIN	Cost MIN
HEV	[100, 400]	[0.001, 0.035]	[0.1, 0.3]	[0.1, 0.5]	[0.3, 1.1]	[17.55, 18.75]
Av-BEV	[125, 300]	[0.035, 0.135]	[0.18, 0.7]	[0.1, 0.4]	[0.18, 0.6]	[18, 19.05]
Re-BEV	[25, 80]	[0.005, 0.018]	[0.05, 0.15]	[0.05, 0.1]	[0.05, 0.15]	[18.8, 19.4]
LPG	[125, 450]	[0.007, 0.035]	[0.17, 0.37]	[0.5, 1.2]	[0.18, 0.65]	[19.2, 22.2]
CNG	[120, 420]	[0.01, 0.025]	[0.05, 0.2]	[0.49, 1]	[0.5, 1.5]	[14.8, 16.6]
Petrol	[125, 500]	[0.01, 0.035]	[0.1, 0.4]	[0.49, 1]	[0.4, 1.42]	[16.8, 19.2]
Diesel	[115, 430]	[0.01, 0.06]	[0.25, 0.62]	[0.2, 0.5]	[0.15, 0.62]	[12.5, 13.9]
Bioethanol	[80, 350]	[0.023, 0.12]	[0.38, 1.2]	[1, 3.5]	[0.19, 0.48]	[14.3, 17]
Biodiesel	[70, 300]	[0.005, 0.07]	[0.44, 1.1]	[0.2, 0.75]	[0.38, 1.2]	[12.5, 13.8]

Table 4
The weight vectors employed for assessment of road transport technologies.

Approaches	Emission criteria					Cost
	GHG	PM10	NO_x	CO	HCs	
Equal weights	0.1	0.1	0.1	0.1	0.1	0.5
Environmental	0.16	0.16	0.16	0.16	0.16	0.2
Consumer	0.04	0.04	0.04	0.04	0.04	0.8

private costs. LPG, however, was placed at the very end of ranking by holistic and environmental approaches.

5. The road infrastructure impact on GHG emissions from road transport

The extent, capacity, and quality of transportation infrastructure affects the overall level of transportation activity, which in turn affects how much energy is consumed for transportation and the amount of greenhouse gases (GHG) emitted. There has been a significant amount of research on whether building new roads increases or decreases GHG emissions. Most studies prove that the new roads decrease vehicle GHG emissions and argue that new roads (at least in the short term) alleviate congestion and move traffic from “rougher” to “smoother” roads, which decreases idling, and helps vehicles keep their amount of fuel used per distance as low as possible [20–26]. A study [20] by the American Highway Users Alliance concluded that in urban areas highway widening projects have impact on alleviating congestion, however for CO_2 benefits to materialize, any increase in highway capacity also required additional strategies, including smart urban planning, increasing public transit capacity, timely highway maintenance, and innovative strategies like congestion pricing. Another study [21] looking at the long-term impacts of new highway construction, has concluded that new roads have a significant negative impact on GHG emissions over their useful life. The study conclude that new roads not only are responsible for induced traffic on roads as people switch from an old road to a new road, but also for generated traffic as some people start driving or drive more because of the availability of a new road. According to a study conducted by the Sightline Institute [22], for every new lane-mile of highway built, CO_2 emissions from vehicle use will increase by 113–183 t over the 50-year life of that road. The study found that while additional highway lane-miles would temporarily provide a net congestion relief (equal to 7000 t of CO_2), this net benefit would be more than canceled out by future net additional vehicle miles travelled (VMT), both on the highway and on surrounding roads, due to increases in population densities and increased average driving distances around new highways. This study has been supported by similar findings by the Victoria Transport Policy Institute in Canada [24]. If every additional mile of highway contributes 113,000–183,000 t of CO_2 over 50 years, then the 50-year impact of $30 billion in new highway miles would be an additional 131–213 million metric tons of CO_2, excluding construction GHG emissions.

Many studies proved that the physical maintenance of roads has positive (decreasing) impact on GHG emissions. Though the materials and construction equipment needed to provide maintenance have impact on increase of life cycle GHG emissions this negative impact on GHG emissions is negated by the positive impact of well-maintained roads on vehicle GHG emissions. A study by the Missouri Department of Transportation [23] found that the road smoothing program for 5600 miles of state highways saved drivers 2.4% in fuel costs. An Ontario, Canada study found that a road smoothing program can reduce the CO_2 emissions from a well-travelled road by 30,000 kg per mile per year [26]. At the highest end of the fuel-saving spectrum, a test study in Norway found that road maintenance can reduce GHG emissions by as much as 38% [21]. ICF used the findings of the Ontario, Canada study, estimating that for a well-travelled road (5000 + vehicles/day), road maintenance can reduce CO_2 emissions by 30,000 kg per mile per year. If $30 billion of the state funding were spent on road maintenance and repair, ICF estimates that the positive GHG reductions could be 2 million metric tons of CO_2 over 50 years [20].

The study conducted by C. Raborn in USA [23] showed that GHG emissions from travel activity are not significantly influenced by overall transportation infrastructure spending. The GHG emissions from construction and maintenance activities are larger than cumulative emissions from changes in travel activity. Increasing infrastructure spending by $30 billion per year from 2011 to 2020 in US a 62% increase over current spending resulted in a decrease of 0.17% in cumulative GHG emissions from current trends. Results from study showed that GHG emissions from the maintenance and construction activities resulting from significantly different levels of transportation infrastructure spending have only a negligible effect on total GHG emissions reduction from transport. A. Strand from Institute of Transport Economics conducted similar study in Norway [21]. The study concluded that the question of whether better roads contribute to lower GHG emissions must be answered mainly negatively. In most cases, the construction of better roads leads to increased GHG emissions as improved road quality facilitates faster driving, often at speed levels where faster driving causes emissions to increase considerably (above 80 km/h). Emissions also increase because people make on average more and longer trips, and because improved conditions for car travelling cause some previous trips by public or non-motorised modes of transport to be replaced by trips by car. Moreover, the road construction itself and the operation and maintenance of the expanded roads require energy use and thereby contribute to increase GHG emissions.

Table 5
Normalized weighted decision matrix and ideal solutions.

HEV	[0.009, 0.034]	[0, 0.016]	[0.005, 0.014]	[0.002, 0.012]	[0.01, 0.036]	[0.121, 0.129]
Av-BEV	[0.011, 0.026]	[0.016, 0.062]	[0.009, 0.033]	[0.002, 0.009]	[0.006, 0.02]	[0.124, 0.131]
Re-BEV	[0.002, 0.007]	[0.002, 0.008]	[0.002, 0.007]	[0.001, 0.002]	[0.002, 0.005]	[0.129, 0.134]
LPG	[0.011, 0.038]	[0.003, 0.016]	[0.008, 0.018]	[0.012, 0.028]	[0.006, 0.022]	[0.132, 0.153]
CNG	[0.01, 0.036]	[0.005, 0.011]	[0.002, 0.009]	[0.011, 0.023]	[0.017, 0.05]	[0.102, 0.114]
Petrol	[0.011, 0.043]	[0.005, 0.016]	[0.005, 0.019]	[0.011, 0.023]	[0.013, 0.047]	[0.116, 0.132]
Diesel	[0.01, 0.037]	[0.005, 0.027]	[0.012, 0.029]	[0.005, 0.012]	[0.005, 0.021]	[0.086, 0.096]
Bioethanol	[0.007, 0.03]	[0.011, 0.055]	[0.018, 0.057]	[0.023, 0.081]	[0.006, 0.016]	[0.098, 0.117]
Biodiesel	[0.006, 0.026]	[0.002, 0.032]	[0.021, 0.052]	[0.005, 0.017]	[0.013, 0.04]	[0.086, 0.095]
A+	0.0021	0.0005	0.0024	0.0012	0.0017	0.0861
A−	0.0426	0.0617	0.0568	0.0808	0.0497	0.1529

Table 6
Closeness coefficients (CC) and ranks for energy technologies.

Technologies	Equally important criteria		Environmental approach		Customer–first approach	
	CC	Rank	CC	Rank	CC	Rank
HEV	0.701	2	0.700	2	0.498	5
Av-BEV	0.606	7	0.605	8	0.456	8
Re-BEV	0.900	1	0.890	1	0.456	7
Petrol	0.678	4	0.674	4	0.344	9
Diesel	0.642	5	0.642	5	0.643	3
Bioethanol	0.624	6	0.624	6	0.488	6
Biodiesel	0.682	3	0.683	3	0.812	1
LPG	0.474	9	0.474	9	0.587	4
CNG	0.606	8	0.607	7	0.777	2

Better traffic management has the potential to deliver significant CO_2 reductions up to 40% by reducing the incidence of stop-go traffic and discouraging excessive speed [23]. Freeing capacity through traffic management will induce additional traffic in many circumstances but even when overall travel increases emissions may still be less than before if operating speeds are more efficient. Mobility management initiatives, landuse planning and promotion of high quality public transport can all help to reduce GHG emissions. These measures will deliver relatively less CO_2 reduction over time as perkilometre CO_2 emission rates decrease due to technical efficiency improvements. Congestion can be abated through enlarging traffic capacity at bottlenecks, adding new capacity more generally and managing existing capacity better, for example through the application of information and communications technologies. These strategies have the potential to deliver important CO_2 reductions if care is taken to avoid induced traffic effects. Even in some cases where overall travel increases, emissions may still be less than before due to more efficient operating speeds. Reducing CO_2 emissions through the promotion of smoother driving styles can reduce emissions by up to 15% at very low cost though the impact of these measures decrease over time without additional training. Promoting eco-driving through new driver training and onboard gearshift and fuel economy metering can help. The smoother or eco driving facilitated by better road standard can, other things equal, contribute to a reduction in emissions of between 5% and 15% [25]. Another important source of behaviour related to CO_2 reduction is through increased load factors for passenger (through high occupancy lanes or toll lanes, carpooling, etc.) and, especially, freight transport [26,27]. In Table 7 the impact of various policies and measures on GHG emission reduction in transport is presented and compared with GHG emission reduction impact from switching to motor vehicles having the lowest GHG emissions (biodiesel from vegetable oil).

As one can see from Table 7 road maintenance, eco driving and traffic management policies can significantly impact GHG emissions from motor vehicles. Therefore comparative assessment of transport technologies based on external costs of GHG emission and private costs presents just one issue of climate change mitigation policy related with promotion of advanced road transport technologies having the lowest costs. Other policies are also able to contribute significantly to GHG emission reduction in transport.

6. Policy implications

Comparative assessment of road transport technologies performed in this paper indicated that in 2050 the low carbon transport technologies will be competitive because of high carbon price. Factoring carbon costs into the prices for transport provides incentives for community to be either more energy efficient or to opt for lower carbon alternatives. It also sends the right long-term signals for investment and makes ultra-low carbon vehicles more competitive for consumers. Therefore it is necessary to integrate external costs of GHG emissions into market and to send a clear signal to industry about the pace of change that is required. Regulating in this way can play a critical role in supporting the transition to low carbon vehicles by establishing a clear, long-term framework for action by industry. Fiscal measures primarily play an important role in ensuring the stability of the public finances but can also have a significant impact on CO_2 emissions from transport. They can lead to cuts in CO_2 by, for example, incentivizing fuel-efficient vehicle purchases, encouraging more fuel-efficient behavior and potentially encouraging lower carbon transport choices. Fiscal measures, such as fuel duty, company car tax, vehicle excise duty and air passenger duty provide these price signals to businesses and consumers. Not just fiscal measures but also tightening vehicle standards and leading research, development and demonstration of low carbon vehicles can have positive impact on penetration of low carbon vehicles into market.

Though innovations in road transport technologies provide highest potential for GHG emission reduction there are other important policies targeting GHG emission reduction in transport: improvement in road infrastructure, traffic management, spatial planning; eco driving etc. These policies implemented together can provide for significant GHG emission reductions at lower costs comparing with implementation of advanced transport technologies having high private costs.

There is a strong and complex relation between infrastructure policy, spatial policy and transport. Infrastructure is an enabler for transport. Additional infrastructure creates additional transport as it reduces travel cost and time. It affects modal split and location choices. Spatial policy has also effects on transport volume and modal choice. Traffic speed policy directly impacts on vehicle GHG emissions. Therefore the investments in road

Table 7
The impact of fuel switching and other policies on GHG emission reduction from road transport.

	The average CO_2 g/vehicle km	The impact of switching to biodiesel (vegetable oil) on GHG emission reduction, CO_2 g/km	The impact of various policies on GHG emission reduction in road transport, CO_2 g/km			
			The impact of eco-driving on GHG emission reduction (15%);	Road maintenance impact on GHG emission reduction; (38%)	The impact of traffic management system on GHG emission reduction (40%)	Total
HEV	186	150	28	71	74	173
PHEV 30	154	118	23	59	62	144
PHEV 60	143	107	22	54	57	133
PHEV 90	140	104	21	53	56	130
Petrol	268	232	40	102	107	249
Diesel	247	211	37	94	99	230
Bioethanol from sugar beet	112	76	17	43	45	105
Bioethanol from wheat	60	24	9	23	24	56
Biodiesel from rapeseed	115	79	17	44	46	107
Biodiesel from waste vegetable oil	36	–	5	14	14	33

infrastructure improvement need to be accompanied by other policies: mobility management initiatives, eco driving and smart transportation practices, application of information and communications technologies; landuse planning and promotion of high quality public transport etc.

The recommended policy options and practical measures for sustainable transport: to promote biofuel technologies especially bioethanol from sugar beet, biodiesel from rapeseed, and biodiesel from waste vegetable by introducing price incentives, improving vehicle emission standards and consumer information; to provide greater incentives for innovation, research and deployment of advanced transport technologies; to enhance research and development in the field of new road transport technologies, sharing of experience, capacity-building and technology transfer; to encourage voluntary initiatives and programmes to offset greenhouse gas emissions from road transport to reduce its net environmental impacts; to improve quality of roads and develop necessary road transport infrastructure; to improve and increase public transport options in congested urban areas; encourage the avoidance or reduction of unnecessary transport and travel via behavioral change measures; facilitate walking and non-motorized transport in urban centers through appropriate planning and infrastructure; to improve efficiency in fuel use by promoting lighter vehicle weight, aerodynamic designs, fuel-efficient tires, engine efficiency improvement; to strengthen transport infrastructure and services by enhancing transport data collection and analysis and modern information technologies.

7. Conclusions

The multi-criteria assessment of energy technologies for road transport was carried out. Hence, road transport technologies were ranked with respect to five emission indicators and private cost criterion. In order to check the sensitivity of the results, the three weight sets were defined: (1) both types of the criteria were considered equally important; (2) for environmental approach the most of significance, namely 80%, was given to emission reduction and (3) for consumer-oriented approach the greatest significance of 80% was attributed to the private cost criterion. The analysis showed that the best option according to holistic (equal weight) and environmental approach is renewable-based battery-electric vehicles (Re-BEV), whereas customers would prefer biodiesel from rapeseed. Indeed, the first two approaches suggest biodiesel as the third-best option.

Analysis of life cycle GHG emissions and private costs of the main road transport technologies including future one indicated that road transport technologies based on biodiesel from waste vegetable oil have the lowest life cycle GHG emission followed by technologies using bioethanol from wheat. Petrol based transport technologies have the highest life cycle GHG emissions followed by diesel technologies. Climate change mitigation policies are necessary for promotion of advanced road transport technologies having the lowest costs. Other policies, i.e. improvement of road infrastructure, traffic management, eco-driving, spatial planning etc. can also significantly reduce GHG emissions from road transport therefore the holistic approach is necessary by developing effective transport policies.

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